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A two-dimensional spectral analysis of short period gravity waves imaged in the OI(557.7 nm) and near infra red OH nightglow emissions over Arecibo, Puerto Rico

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Abstract. In January 1993 an extensive set of radar and optical data was gathered from various key sites around the world during a coordinated "10 Day Run" designed to investigate the coupled dynamic behavior of the upper atmosphere on a large, medium and small scale. As part of this campaign an all-sky CCD imaging system was operated at Arecibo Observatory, Puerto Rico, to help quantify the response of the low latitude mesosphere-thermosphere system to short period (<1 hour) gravity waves. Measurements of the OI(557.7 nm) and near infrared OH nightglow emissions were made in conjunction with photometric and ISR radar soundings and revealed an abundance of small-scale structure in the 80-100 km range. In this letter we apply two-dimensional spectral analysis techniques to aid in the interpretation of a complex set of image data that consisted of two intersecting quasi-monochromatic gravity wave patterns progressing on approximately orthogonal headings. An investigation of the spectral content and temporal evolution of these wave motions at each emission altitude is presented.

Introduction

Image measurements of the naturally occurring nightglow emissions provide an important technique for remote sensing gravity waves in the vicinity of the mesopause. To date most imaging studies have focused on measurements of prominent, quasi-monochromatic wave motions and have revealed significant information on their average horizontal wavelength (λ_h), horizontal velocity (v_h) and their occurrence frequency [e.g. Taylor and Hill, 1991; Swenson and Mende, 1994]. The availability in recent years of sensitive solid state (CCD) imagers now makes it possible to perform a quantitative spectral analysis of the dominant frequency components constituting the quasi-monochromatic wave motions and to assess changes taking place in the wave field that are difficult to measure using conventional spatial analysis methods [Hapgood and Taylor, 1982].

During the AIDA '89 campaign Arecibo was the focus of several gravity wave investigations and the temporal properties of long and short period wave motions were measured in considerable detail [e.g. Wiens et al., 1993; Kieffaber et al., 1993]. However, image measurements during this campaign were somewhat limited by seeing conditions and detector sensitivity [Hecht et al., 1994]. As part of the January 1993 "10 Day Run" campaign a large field, monochromatic CCD imager capable of detecting faint structure in the nightglow emissions was field tested at Arecibo. Measurements were made of the OI(557.7 nm) nightglow line emission, which originates at a mean height of ~96 km, and of the near infrared (NIR) hydroxyl (OH) band emissions, which arises from a well-defined layer centered at ~87 km. Observations of these two emissions provide an effective mechanism for investigating the penetration of wave energy from the mesosphere into the lower thermosphere. The observing conditions at the optical site were good and a wealth of small-scale, short period structure was recorded. Here we analyze a particularly interesting set of waves imaged on the night of 21 January. A comparison of these data with the ISR radar measurements will be the subject of a separate report.

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Instrumentation

An all-sky (180°) CCD imaging system comprising an AT200 digital camera (on loan from Photometrics Co.) and an f/4 telecentric lens arrangement (supplied by Keo Consultants) was installed at Arecibo Observatory, Puerto Rico (18.35°N, 66.75° W) in mid January 1993. The camera utilized a Kodak KAF-4200 array (area 3.4 cm^2) cooled to -40°C (dark current ~0.12 e^- /pix/s). Structure in the OI(557.7 nm) emission was isolated using an interference filter of halfwidth 2.4 nm. Observations of the NIR OH emission were made using a broad band filter (715-930 nm halfwidth) with a notch at ~865 nm to suppress contributions from the $O_2(0,1)$At band emission (courtesy of G. Swenson). Filters were changed manually at intervals during the night and images of the selected nightglow emission were recorded every three minutes. Exposure times of 15s for the OH signal and 120s for the fainter OI emission were determined. Each image was 4x4 binned to 512 x 507 pixels and digitized to 12 bit resolution.

Observations

Observations were made during the new moon period 16-29 January, 1993. The large field of view (>750,000 km^2) and the high spatial resolution (~0.6 km in zenith) provided an excellent capability for remote sensing small-scale gravity waves within a ~500 km radius of Arecibo. On 21 January measurements were made primarily of the OI (557.7 nm) emission. Figure 1a shows an extensive, well defined wave motion imaged in the OI emission at 06:05 UT. Many (>12) regularly spaced, linear wave crests are seen extending over the entire field of view. These waves were observed for over 5 hours progressing uniformly towards the SW and are a good example of what is commonly termed a quasi-monochromatic wave pattern. In this paper we

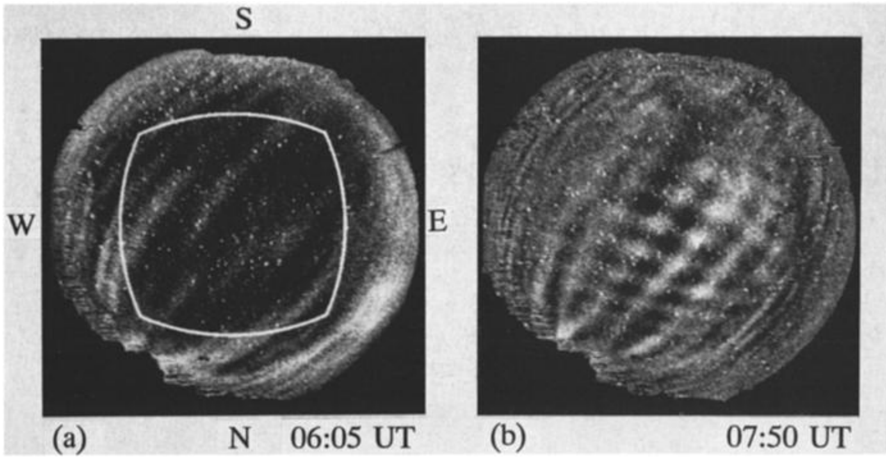

Figure 1. Two examples of extensive quasi-monochromatic gravity wave patterns imaged on 21 January in the OI(557.7 nm) emission: (a) shows a single wave pattern progressing towards the SW, (b) shows a more complex wave pattern resulting from the addition of a second wave motion progressing towards the NNW. Both images have been flat-fielded to enhance the wave structure. The white border in (a) indicates the 256 x 256 km^2 spectral sample region.

refer to this pattern as the "primary" wave but, as will be shown later, this disturbance actually consisted of two distinct spectral components. During the course of these measurements a second quasi-monochromatic wave was observed over Arecibo progressing towards the NNW. Figure 1b shows an OI image at 07:50 UT when these two disturbances were present simultaneously. At this time both wave motions occupied a large part of the camera's field and are seen to intersect almost at right angles resulting in a marked cross-hatch pattern. By 08:10 UT the second wave had faded considerably but images of this wave motion could still be made in the OH emission and were recorded for the next ~70 min. In total over 80 OI images and 25 OH images of this complex display were recorded.

Spectral Analysis and Results

To quantify the morphology and dynamics of these two quasi-monochromatic waves a spectral analysis of the data was performed using a two-dimensional discrete Fourier transform. A full description of the analysis method will be presented elsewhere. Briefly, a "background" was created for each image by removing the brightest stars and averaging together a series of 11 pictures centered on the image to be processed. These backgrounds were then used to flat-field the image data set. To a good approximation this process removes the unwanted contributions of lens vignetting and line-of-sight (van Rhijn) enhancement at low elevations from the data. The data shown in Figure 1 are examples of images flat-fielded in this manner. To eliminate geometric effects introduced by the all-sky image format, the data were then mapped onto the earth's surface and re-sampled using bilinear interpolation with a grid size of 0.5 km. The area of the image mapped in this process is indicated by the white border in Figure 1a and corresponds to a 256 km x 256 km region of the overhead sky. A two-dimensional Fourier analysis of the resultant image data was then performed to determine the parameters (λ_h,v_h) of the wave components and their directions of propagation.

Figure 2 plots the 2-d power spectral density (PSD) for the OI data of Figure 1. The horizontal wave numbers k_x and k_y indicate the position of the spectral peaks while the vertical axis indicates the power of each spectral component. It is clear that the primary wave disturbance (Figure 2a) consisted of not one but two distinct wave components of differing horizontal wavelengths propagating towards the SW at azimuths separated by < 20° (see Table 1). This is illustrated further in Figure 2c which shows a plan view of the k_x-k_y domain. The peak amplitudes of the two wave components are similar but the longer wavelength component (closer to the origin) has a significantly broader spectral width. At this time there is no evidence of the second wave disturbance.

In comparison, Figure 2b shows two distinct peaks corresponding to the primary and the second wave motions imaged in Figure 1b. The corresponding k_x-k_y map (Figure 2d) shows that the primary disturbance is now dominated by a single component at the same frequency as the shorter wavelength component imaged ~2 hours earlier. The second wave disturbance is near monochromatic and exhibits a distinct but significantly smaller amplitude peak. The dynamics of the second wave are illustrated in Figure 3 which shows a series of six consecutive k-space diagrams plotted at 3 minute intervals. The apparent growth and decay of the second wave over a limited period (~20 min) is clearly shown. Shortly after the second wave faded in the OI data the filter was changed and sequential measurements

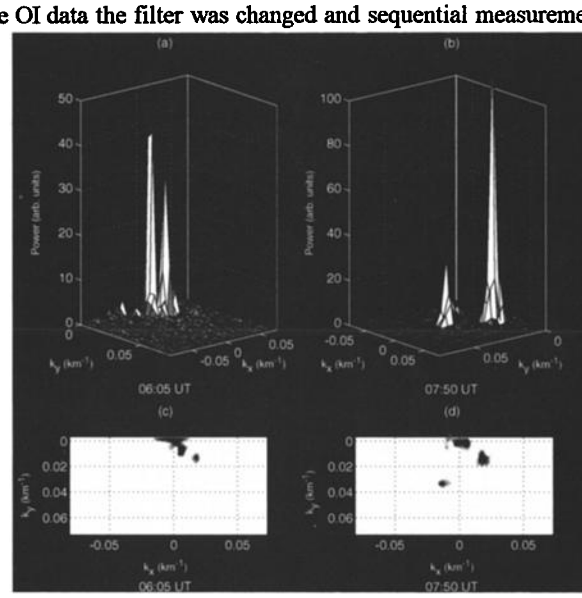

Figure 2. Two-dimensional power spectral density plots (PSD) for the OI images of Figure 1. In (a) the adjacent peaks correspond to the two wave components of the primary wave. In (b) the components show the position and relative power of the second wave and the persistent primary wave component. Plots (c) and (d) show plan views of the k_x-k_y plane indicating the relative positions of the spectral components.

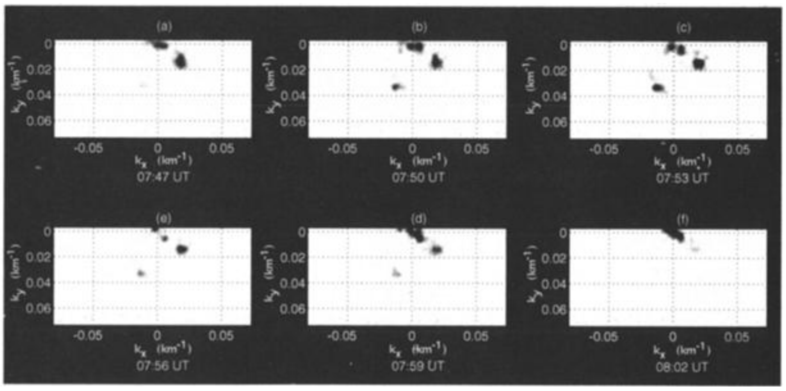

Figure 3. K-space plots showing the growth and decay of the second wave disturbance in the OI emission.

of the NIR structure revealed that both these wave motions were still present at the OH emission altitude. Figure 4 shows a PSD for the OH data at 08:31 UT. Spectral measurements of the OH emission were more difficult due to the larger bandwidth of the filter (resulting in more background noise) but nevertheless three distinct peaks are seen corresponding to the two primary wave components and a strong second wave motion.

From the peak locations in k space the horizontal wavelength and the direction of motion of each wave component was determined. Their apparent phase speeds were then found by plotting the phase of each spectral peak as a function of time. Figure 5 shows the results for the persistent primary wave component and for the second wave. The uniform gradient in plot (a) indicates a constant phase speed for the primary wave component throughout the night. However, phase estimates for the second wave motion (plot b) became consistent only after ~06:30 UT when the coherence of the wave motion was observed to increase. A summary of the OI and OH wave measurements for this night is given in Table 1. Although the two OI primary wave components have markedly different horizontal wavelengths, their observed periods (τ_{ob}) were comparable at 25-28.5 min and approximately twice that of the second wave motion. Similar values were determined for the wave components at OH heights but due to the increased background in this emission it was not possible to identify these parameters as accurately as in the OI data.

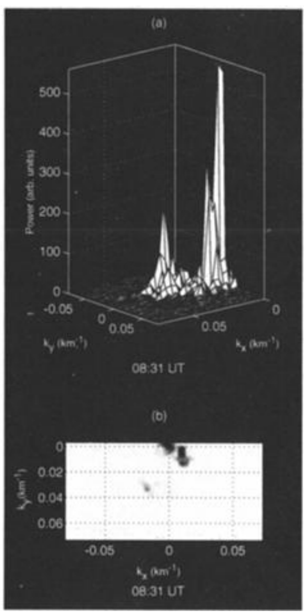

Figure 4. PSD plot for the OH data recorded at 08:31 UT. Three distinct peaks are seen corresponding to the two primary wave components and the second wave.

Discussion

Spectral measurements have revealed the frequency content of the quasi-monochromatic wave patterns present in the mesosphere and lower thermosphere on this night. Two important results are:

- identification of two distinct wave components in the primary disturbance, and
- determination of the temporal evolution of the primary and the second wave motions.

Extensive quasi-monochromatic motions similar to the primary wave pattern shown here are a common occurrence [e.g. Swenson and Mende, 1994; Taylor et al., 1994]. These patterns often display good spatial uniformity and temporal coherence (as in this case) and conventional measurements have been used to good effect to determine mean values for their horizontal parameters [Taylor and Hill, 1991]. However, these patterns may also exhibit temporary non-uniformities in the wave field such as bifurcations or truncations (see Figure 1a) that are averaged out when using conventional spatial analysis techniques [Hapgood and Taylor, 1982]. In comparison, this spectral study has revealed the true frequency content of the wave field and clearly shows that much of the temporal and spatial variability may be attributed to the presence of more than one wave component. In this case the primary wave pattern detected in the OI and the OH emission layers consisted of two waves of markedly different horizontal wavelengths but comparable periodicities propagating at similar azimuths (within 20°).

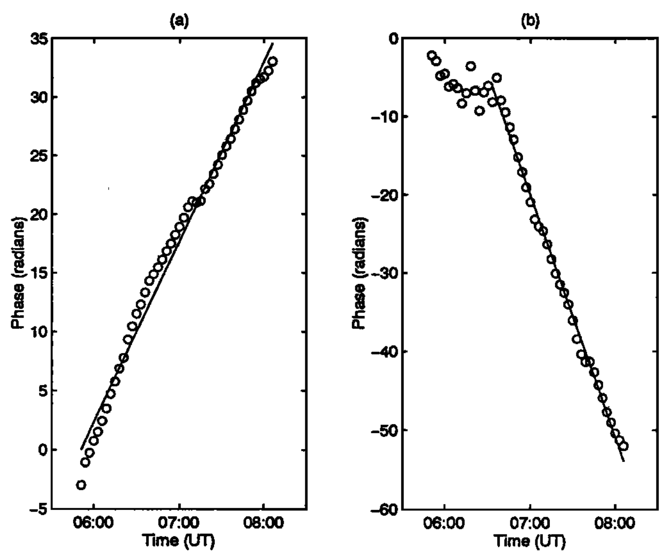

Figure 5. Phase of the peak as a function of time for (a) the persistent primary wave component, and (b) the second wave.

Table 1. Horizontal wave parameters derived from spectral analysis of the OI and OH image data.

Emission	Spectral Peak	k_x (km^{-1})	k_y (km^{-1})	Azimuth (°N)	λ_h (km)	v_h (ms^{-1})	τ_{ob} (min)
OI	Primary	0.0078	0.012	218	70	41	28.5
OI	Primary (persistent)	0.02	0.016	236	39	26	25
OI	Secondary	-0.012	0.035	346	27	37	12
OH	Primary	0.0076	0.012	243	70	34	34
OH	Primary (persistent)	0.012	0.015	224	47	31	25
OH	Secondary	-0.016	0.035	341	26	40	11

This result has implications on the sources of these types of gravity waves many of which are considered to be tropospheric in origin. The extensive, near linear nature of the wave field is indicative of an extended source such as a front or a jet stream located to the NE of Arecibo. The similarity in periodicity of the two wave components and their close propagation azimuths suggest that wave generation may have occurred at different locations within the same source region. Temporal analysis of these data has also revealed that the wave components varied considerably in amplitude with time and that the longer wavelength primary component was sometimes absent for extended periods of time (e.g. Figure 2b). Wind filtering in the middle atmosphere may have had an important influence on the observed wave variability. However, it is also possible that the source of the longer wavelength component may have been less persistent than that of its companion. The appearance of a second quasi-monochromatic disturbance propagating almost perpendicularly to the primary wave components indicates the presence of another source region, located to the ~SSE of Arecibo. Both of these disturbances were detected in the OH and OI layers (mean separation ~10 km) suggesting that wave energy was able to propagate from the mesosphere into the lower thermosphere on this occasion. Furthermore, the power in the primary OI wave component (not shown) was observed to increase considerably during the course of the night by a factor of ~5 times corresponding to a marked growth in its visibility and contrast. In comparison, the second wave exhibited very little power prior to 06:30 UT and was most contrasted over an hour later around the time of Figure 1b.

In summary, spectral analyses of nightglow image data are rare and these measurements constitute the first detailed investigation of quasi-monochromatic wave motions imaged in the OI emission. CCD data may also be used to investigate the two-dimensional horizontal wave number spectrum [Hecht et al., 1994]. Recent studies indicate that the shape of this spectrum should be influenced strongly by the characteristics of the lower atmospheric wave sources [Gardner, 1994]. A detailed study of the slope of the wave spectrum will be presented at a later date.

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